Gamow-Teller Strength Deduced from ^{54}Fe$(n,p)^{54}$Mn Cross Sections at 298 MeV

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Gamow-Teller (GT) strength has been extracted from cross sections for the reaction ^{54}Fe$(n,p)^{54}$Mn at 0°, 2.5°, 5°, 8°, and 12°, and for an incident energy of 298 MeV. This determination of the β^+ GT strength S_+ allows for the first time a full test of the Ikeda sum rule. These data also show that the best available shell-model calculations overestimate this strength by a factor of 2. This result is significant in models of supernovae since electron capture in (fp)-shell nuclei, which is proportional to S_+, depletes the relativistic electron gas in precollapse stars.

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Charge-exchange reactions at small momentum transfer have been very useful for the study of β-decay strength distributions, especially in states for which β decay is not energetically possible.[1,2] In particular, $V_{\sigma\tau}$, the spin-isospin–flip component of the nucleon-nucleus interaction, dominates over V_τ, the non-spin-flip component, suppressing Fermi transitions in (p,n) reactions above about 100 MeV incident energy. Furthermore, because of the neutron excess in nuclei, isospin selection rules do not allow Fermi transitions in (n,p) reactions. Therefore, intermediate-energy nucleon charge-exchange reactions are excellent filters of Gamow-Teller (GT) strength ($\Delta T=1$, $\Delta S=1$, $\Delta L=0$, $0\hbar\omega$ excitations) since their 0° cross section is proportional to B(GT), the β-decay strength.

These reactions can be used to test the sum rule[3]

$$S_- - S_+ = 3(N-Z),$$

where S_- is the integrated GT strength in β^- decay, which is related to the 0° (p,n) cross section, S_+ is the integrated GT strength in β^+ decay, related to 0° (n,p) cross sections, and $N-Z$ is the neutron excess of the target. Previous (p,n) results have suggested that as much as 40% of the sum-rule strength is missing. This factor is common to nuclei spanning the periodic table.[4] The value of 40% assumed $S_+=0$ because of Pauli blocking in neutron-rich nuclei, since there was essentially no experimental information on S_+ until now.

In this Letter, we present results for the reaction ^{54}Fe$(n,p)^{54}$Mn which, when combined with the ^{54}Fe$(p,n)^{54}$Co results of Rapaport *et al.*,[5] will allow the first full test of the sum rule. GT excitations are not blocked in the (n,p) $(\Delta T_z=+1)$ case because of the $\pi(f_{7/2})$ to $\nu(f_{5/2})$ transition. Indeed, GT strength has been observed in the reaction ^{54}Fe$(t,{}^3$He$)^{54}$Mn at 25 MeV.[6] We will also show that shell-model calculations by Bloom and Fuller[7] and by Muto[8] overestimate S_+ by at least a factor of 2. This result is of interest in astrophysics since S_+ is related to electron-capture rates in (fp)-shell nuclei which influence the electron-to-baryon ratio Y_e in stars prior to gravitational collapse. In turn, Y_e influences the mass of the core which will collapse.[7]

Cross sections for ^{54}Fe$(n,p)^{54}$Mn were measured at five angles between 0° and 12° with use of the charge-exchange (CHARGEX) facility of the TRIUMF medium-resolution spectrometer (MRS). Nearly monoenergetic neutrons with an energy of 298 MeV were produced by the reaction ^{7}Li$(p,n)^7$Be. The proton beam was swept away by a compact dipole magnet into a shielded beam dump. The secondary neutron beam then struck targets located at the pivot of the MRS. Protons from the (n,p) reaction were analyzed by the spectrometer in the usual way[9] with the addition of a second front-end wire chamber to provide better ray tracking back to the target. The CHARGEX facility is described in more detail elsewhere.[10] The target consisted of six layers separated by wire planes. By consideration of the pattern of hit wires in these planes, it was possible to determine in which layer the (n,p) reaction occurred. Corrections were made for the energy loss in subsequent target layers in order to recover good resolution (≈ 1 MeV). This technique allows the use of a thick segmented target or the simultaneous acquisition of data from different target types. A full description of the target box can be found elsewhere.[11] The configuration used for this experiment was as follows: empty, ^{12}C (46 mg/cm^2), empty, ^{54}Fe (140 mg/cm^2), ^{54}Fe (140 mg/cm^2), CH_2 (47.2 mg/cm^2). The empty-target locations were used to determine the contribution to the spectra from the wire-chamber gas and windows. The

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isolated peak from the $^1H(n,p)$ reaction in CH_2 provided the means for normalization, simultaneously collected with the data from the primary targets. A value of 53.6 mb/sr in the lab frame was assumed for this cross section at 0°; this was obtained from the Arndt 1986 phase shifts.[12] The carbon contribution was subtracted from the CH_2 spectrum to obtain the energy profile of the incident neutron beam. The latter exhibited a low-energy tail, of intensity ≈ 1 %/MeV of the nearly monoenergetic neutron peak, which was unfolded from the data.

Results for the $^{54}Fe(n,p)^{54}Mn$ cross section at 298 MeV are shown in Fig. 1. Of note is the strongly forward-peaked feature below 10 MeV excitation. This is the Gamow-Teller resonance and its location and shape are reasonably well reproduced by the calculation of Bloom and Fuller[7] (see the 0° spectrum). Although the theory agrees qualitatively with the data, it must be renormalized to fit the magnitude of the peak.

The $\Delta L=0$, GT component of the cross section was determined by a multipole decomposition using angular-momentum transfers up to $\Delta L=2$. The data were summed in 1-MeV bins and the resulting angular distributions were fitted by the theoretical curves generated by distorted-wave impulse-approximation (DWIA) calculations[13] with the Love-Franey interaction at 270 MeV.[14] The contribution of each multipolarity was thus determined for each bin. For more details see Moinester.[15] The angular distributions were calculated for simple one-particle, three-hole configurations: $[\pi(f_{7/2})^{-3} \times \nu(f_{5/2})]_{1^+}$ for $\Delta L=0$, $[\pi(f_{7/2})^{-3}\nu(g_{9/2})]_{1^-}$ for $\Delta L=1$, and $[\pi(f_{7/2})^{-3}\nu(f_{5/2})]_{3^+}$ for $\Delta L=2$. These configurations are analogous to those used in the analysis of $^{58}Ni(p,n)^{58}Cu$ by Rapaport *et al.*[5] The Q-value dependence of the shapes was accounted for by calculation of the angular distributions in 10-MeV intervals from 0 to 40 MeV, and interpolation for excitation energies in between. The optical potentials used for the distortions in DW81 were of the Woods-Saxon form and were obtained from $^{54}Fe(p,p)$ elastic data taken at TRIUMF.[16] The results of the decomposition are plotted for 0° in Fig. 2. The low-energy peak is well fitted. However, the decomposition produces a tail at high energy for the $\Delta L=0$ component. The amount of $\Delta L=0$ strength above 10 MeV is uncertain and depends on the assumed shape of the $\Delta L=1$ angular distribution. Since the $\Delta L=1$ contribution dominates between 10 and 30 MeV, it is possible that a small change in the $\Delta L=1$ shape could produce spurious $\Delta L=0$ strength in this region of excitation energy. The integrated cross section below 10 MeV is 16.9 ± 1.1 mb/sr excluding the uncertainty on the $^1H(n,p)$ normalization. Of this, 12.9 mb/sr, or 76%, is

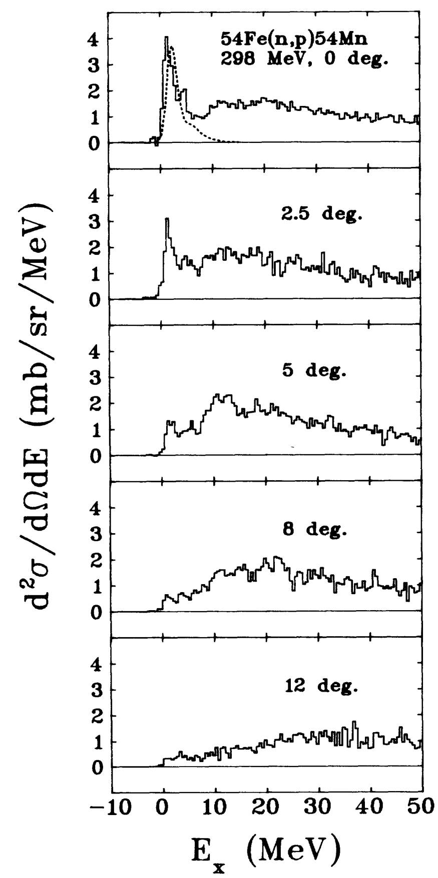

FIG. 1. Cross sections for the reaction $^{54}Fe(n,p)^{54}Mn$ at 298 MeV for five angles between 0° and 12°. The strongly forward-peaked feature below 10 MeV in excitation energy is the Gamow-Teller resonance. The dashed curve in the 0° spectrum is the calculation of Bloom and Fuller (Ref. 7) normalized by a factor of about 0.45.

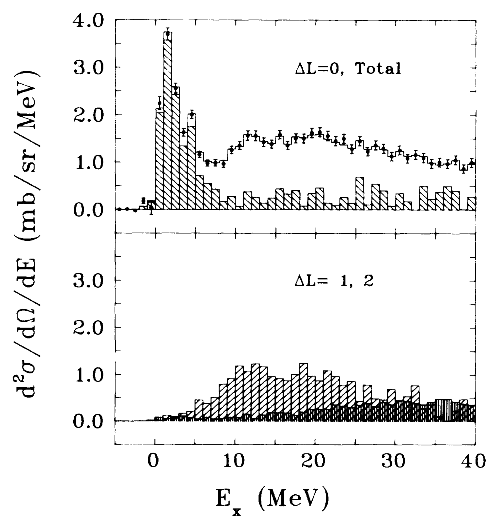

FIG. 2. Multipole decomposition of the 0°, $^{54}Fe(n,p)^{54}Mn$ spectrum. The top graph is a plot of the data with the total fitted curve, as well as the $\Delta L=0$ component shown as the hatched region. The bottom graph shows the $\Delta L=1$ component (cross-hatched region) and the $\Delta L=2$ component (vertically hatched region).

$\Delta L=0$ as determined by the multipole decomposition. Ascribing an error of ± 5 to this percentage because of uncertainties in the shapes of the angular distributions, we get 12.9 ± 1.2 mb/sr for the 0°, $\Delta L=0$ cross section below 10 MeV. We note that the $\Delta L=0$ cross section between 10 and 40 MeV is 8.5 mb/sr. However, since the $\Delta L=0$ component is uncertain above 10 MeV, we will not consider strength above this energy in the present analysis.

Because of the absence of a strong, known β^- decay in the (fp) shell with which to calibrate the (n,p) reaction, the ratio $\sigma(0°)/B(\mathrm{GT}^+)$ of the (n,p) cross section to the β^+-decay strength had to be calculated theoretically. This was done with the computer program OXBASH[17] with the simple $\pi(f_{7/2})^{-3}\nu(f_{5/2})$ configuration to obtain $B(\mathrm{GT}^+)$ and the one-body transition densities needed for input to DW81 which was used to calculate $\sigma(0°)$. As a check, we obtained $\sigma(0°,q=0)/B(\mathrm{GT}^+) \approx 7$ mb/sr for ^{54}Fe at 160 MeV, in agreement with the calculation shown in Fig. 6 of Ref. 2. A further test of the calculation was done at 300 MeV using our data for the $^{12}\mathrm{C}(n,p)^{12}B$(g.s.) transition. The ratio was found to be 7.1 experimentally, as predicted by DWIA. Hence, we can use this method for obtaining $\sigma/B(\mathrm{GT})$ with some confidence. A value of 3.4 was calculated for the ratio $\sigma(0°)/B(\mathrm{GT})$ in ^{54}Fe at 300 MeV. Note that this is not extrapolated to $q=0$ but is simply the ratio at 0°. Using this result, we obtain $S_+ = 3.8 \pm 0.4$. Including a systematic error of 0.6 arising from the uncertainty in the calculation of $\sigma(0°)/B(\mathrm{GT})$, we get $S_+ = 3.8 \pm 0.4 \pm 0.6$. Bloom and Fuller have predicted $S_+ = 9.1$ for a two-particle, four-hole (2p-4h) model.[7] This model includes (1p-1h) excitations from $f_{7/2}$ to $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ in both the parent and daughter nuclei. Muto has done a similar calculation and obtains comparable results ($S_+ = 9.4$).[8] Thus, these calculations overestimate GT strength by a factor of 2.4. A likely cause of the large discrepancy is the severe truncation of the model space used in the calculations. This truncation has more drastic consequences for (n,p) reactions because they are more sensitive to the details of the Fermi surface than either (p,n) or (p,p) reactions. Indeed, in Ref. 8, Muto extends the model space to include 2p-2h excitations in the parent nucleus and calculates $S_+ = 5.1$. However, since 2p-2h excitations are not included in the daughter nucleus, this model does not satisfy the sum rule since $\pi(f_{7/2})$ to $\nu(f_{5/2})$ transitions are not allowed from 2p-2h parent configurations. Using a sum-rule technique which eliminates the daughter wave function from the evaluation of the total GT strength, Muto estimates $S_+ = 7.4$, 20% smaller than the simpler 1p-1h model. However, this still overestimates the experimental value by a factor of almost 2 ($S_+^{(\mathrm{exp})}/S_+^{(\mathrm{th})} = 0.51$). Similar truncation effects have been seen in the (sd) shell by Wildenthal and others.[18] In other studies, Auerbach, Zamick, and Klein[19] and Cha[20] have shown that the use of random-phase-approximation wave functions, instead of the simplest shell model, reduces the calculated GT$^+$ strength by a factor of about 2. Thus, it is crucial to consider the largest possible configuration space in the calculation of GT strength for (fp)-shell nuclei.

As mentioned above, these results are important for models of supernovae because the relativistic electron gas, which resists the gravitational collapse of the star, is depleted by electron capture. Thus, the rate of this capture influences the mass of the core which will collapse and eventually create an outward-going shock wave which may lead to a supernova explosion.

Our result of $S_+ = 3.8 \pm 0.4 \pm 0.6$ can be used in conjunction with the $^{54}\mathrm{Fe}(p,n)^{54}\mathrm{Co}$ result,[5] $S_- = 7.8 \pm 1.9$, to test the sum rule. We get $S_- - S_+ = 4.0 \pm 2.1$. This is 67% of the sum-rule value of 6. However, the large uncertainty also makes $S_- - S_+$ consistent with the sum rule. Angular distributions for the reaction $^{54}\mathrm{Fe}(p,n)^{54}\mathrm{Co}$ at 300 MeV have been measured at TRIUMF.[21] It is hoped that the $\Delta L=0$ component can be extracted realiably from these data, and that the uncertainty in S_- can be reduced. Furthermore, we recall that the possible $\Delta L=0$ (n,p) strength above 10 MeV excitation has been ignored in this analysis. A complete study of the sum rule will also have to take into account this difficult problem.

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